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WHITE-LIGHT MOVIES OF THE SOLAR PHOTOSPHERE FROM THE SOUP INSTRUMENT ON SPACE LAB 2

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ABSTRACT

We present initial results on solar granulation, pores and sunspots from the white-light films obtained by the Solar Optical Universal Polarimeter (SOUP) instrument on Spacelab 2. SOUP contains a 30-cm Cassegrain telescope, an active secondary mirror for image stabilization, and a white-light optical system with 35-mm film and video cameras. Outputs from the fine guidance servo provided engineering data on the performance of the ESA Instrument Pointing System (IPS). Several hours of movies were taken at various disk and limb positions in quiet and active regions. The images are diffraction-limited at 0.5 arc second resolution and are, of course, free of atmospheric seeing and distortion. Properties of the granulation in magnetic and non-magnetic regions are compared and are found to differ significantly in size, rate of intensity variation, and lifetime. In quiet sun on the order of fifty percent of the area has at least one "exploding granule" occurring in it during a 25 minute period. Local correlation tracking has detected several types of transverse flows, including systematic outflow from the penumbral boundary of a spot, motion of penumbral filaments, and cellular flow patterns of supergranular and mesogranular size. Feature tracking has shown that in quiet sun the average granule fragment has a velocity of about one kilometer per second.

INSTRUMENT

The Solar Optical Universal Polarimeter (SOUP) instrument, built by the Lockheed Palo Alto Research Laboratory (LPARL), flew on the Space Shuttle as part of the Spacelab 2 mission from 29 July to 6 August, 1985. SOUP was designed to study granulation, sunspots, magnetic fields and velocity fields in the photosphere. It consists of a 30-cm Cassegrain telescope, white-light film and TV cameras, a birefringent filter tunable over 5100-6600 Å with 0.05 Å bandpass, and 35-mm film and digital CID cameras behind the filter. Figure 1 shows a photograph the instrument and a schematic drawing of the optical system. SOUP and three other solar instruments were pointed at the sun by the European Space Agency Instrument Pointing System (IPS).

Since SOUP required more stable pointing than the one arc second precision of the IPS, it contained its own image motion compensation system. Stabilization was accomplished by a piezoelectrically (PZT) driven secondary mirror whose control signal was generated by a set of solar limb sensors in the primary focal plane.

POINTING

Spacelab 2 was the first flight of the IPS and a quantitative measure of IPS performance was obtained from signals generated by the SOUP image stabilization system. The control loop for the secondary mirror used a high-gain (55 dB at DC), high bandwidth (200 Hz crossover) servo. The PZT system had enough range (±25 arc seconds) to accommodate the largest excursions expected from the IPS. From recordings of the mirror deflection signal, we have determined that the IPS had a quiescent stability, on each axis, of 0.75-1.50 arc second rms and 4-8 arc seconds peak-to-peak. The transients recorded by SOUP, caused by space shuttle thruster firings, produced excursions up to ±10 arc seconds, and rates up to 40 arc seconds/second, with typical recovery times of 5 seconds. The IPS response to a thruster firing at t=5 seconds, which produced about an 18 arc second excursion peak-to-peak, is shown in the top half of Figure 2. The bottom half of the figure shows the motion of the SOUP image as determined by the

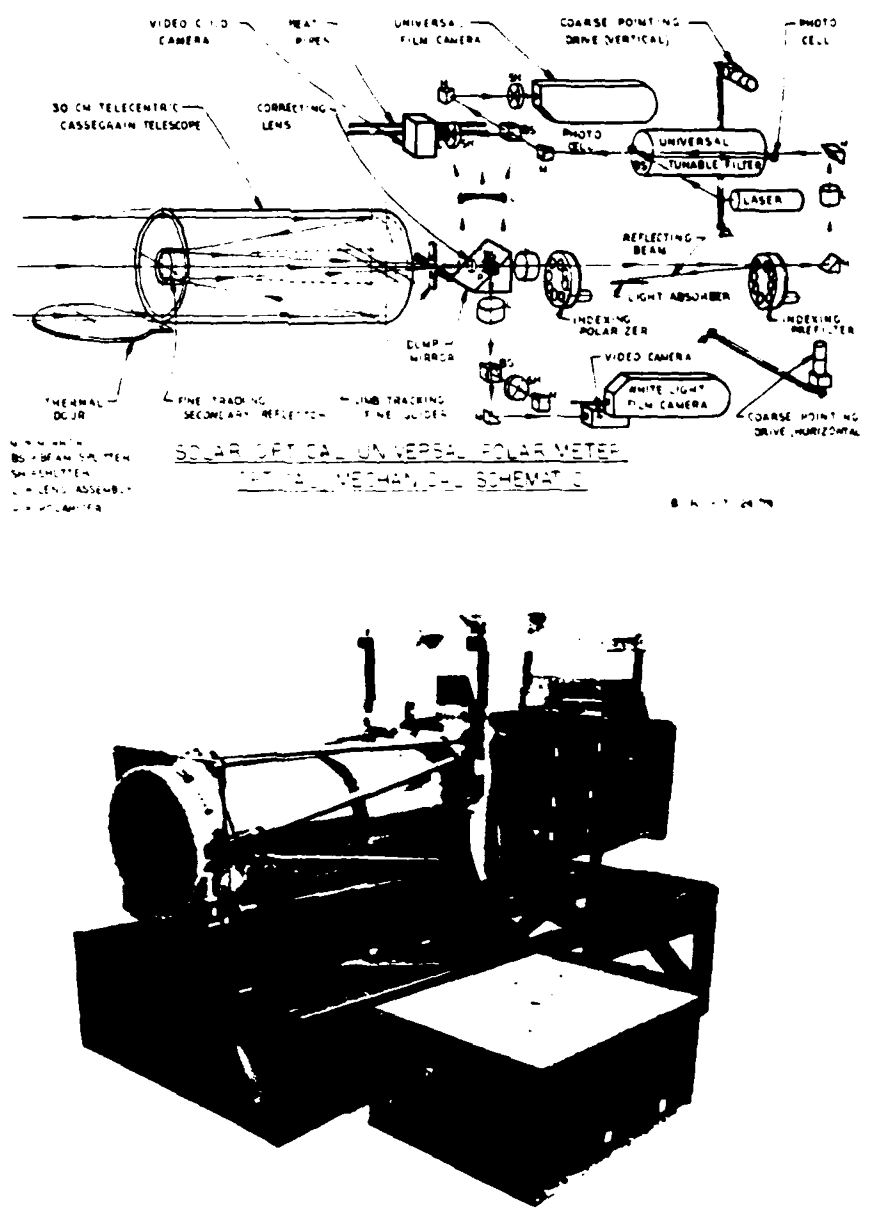

Fig. 1 SOUP Instrument

error signal generated from the limb sensors. The jitter in the instrument focal plane is within an 0.01 arc second band with a peak-to-peak excursion less than 0.04 arc second; i.e., the SOUP fine guidance system improved the stability against such an excursion by a factor of 500. Similar enhancements of quiescent stability resulted in typical residual image jitter of the SOUP image of only about 0.003 arc second rms on each axis.

A portion of the power spectrum of the image motion observed by SOUP is shown in Figure 3. The dominant peak at 1 Hz arises from the basic controller frequency of the IPS command cycle. Weaker resonances at 3.5, 4.5, 5.5, 8 and 14 Hz are believed to be in the IPS and or cruciform, the one at 17 Hz due to the HRTS (Naval Research Lab telescope, and another at 31 Hz (not shown in Figure 3) due to SOUP.

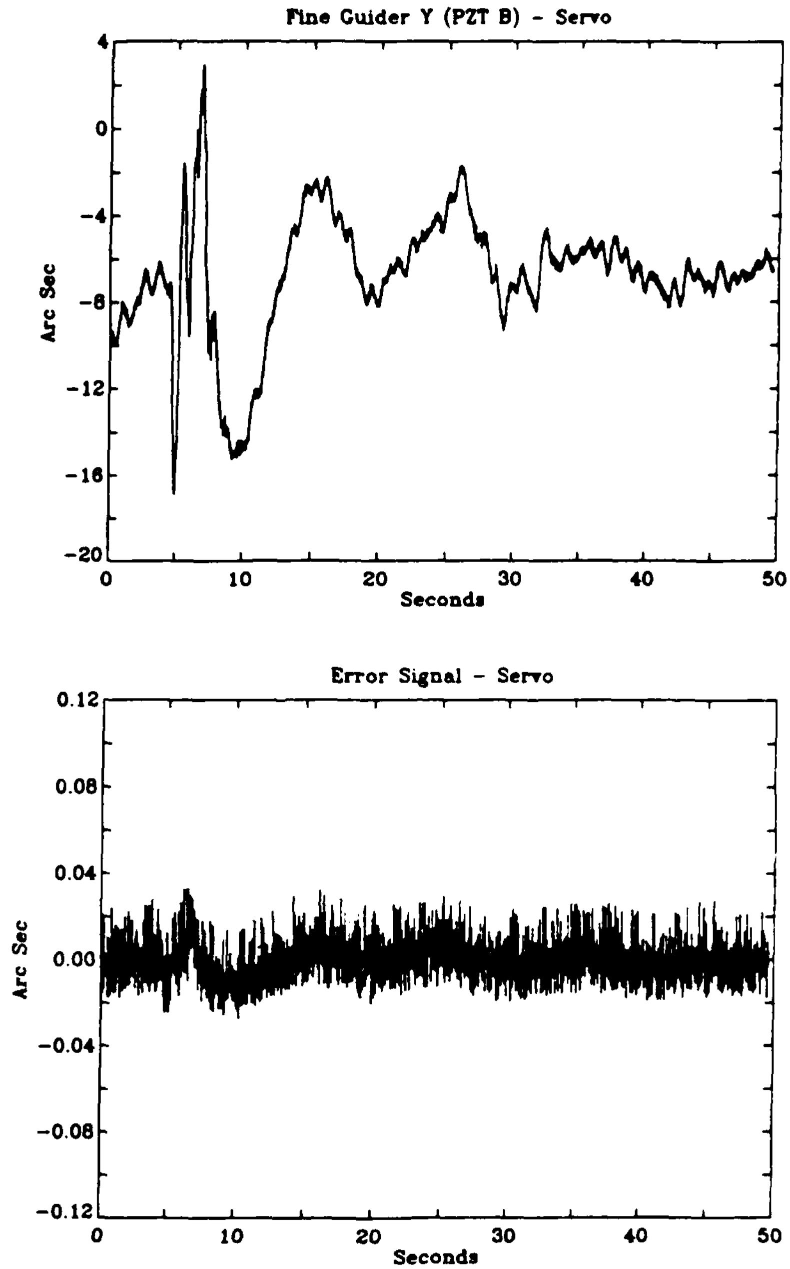

Fig. 2 Image motion before and after compensation

DATA

The image stabilization and white-light optical systems performed extremely well, and several hours of white-light movies were obtained at various disk and limb positions. These data are diffraction-limited at 0.5 arc second resolution and are free of distortions caused by image motion. For most of the data the interval between exposures was 2 seconds. In total, about sixty-four hundred frames of white-light images were obtained. In a typical 90-minute orbit, between 10 and 40 minutes of data were collected.

In this paper we shall discuss results obtained to date from a data set taken in the vicinity of active region 4682 on 5 August, some 850 images obtained every two seconds from 19:10 to 19:38 GMT.

The data were recorded on Eastman Kodak SO 253 film. After development, a high contrast, fine grained

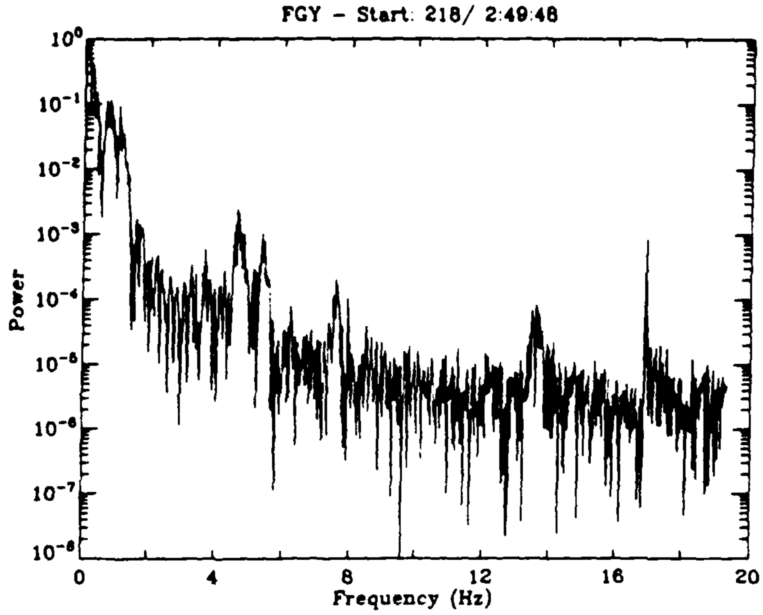

Fig. 3 Power spectrum of image motion

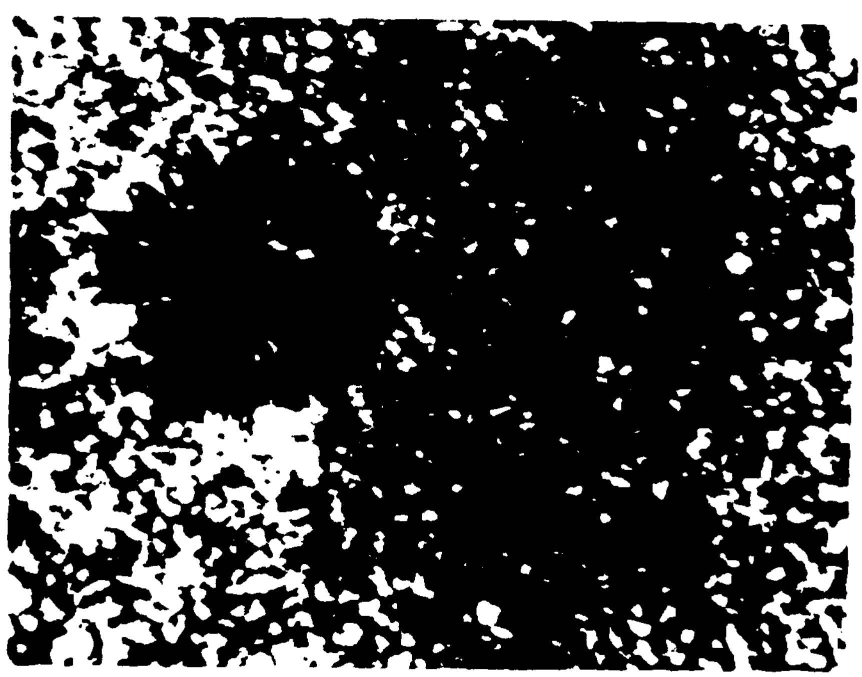

Fig. 4 White-light image, 55 x 71 arc seconds

positive copy was produced. Selected areas (sunspot, pores, quiet sun) of the data from this time interval were digitized using a CCD camera system and recorded on magnetic tape in 512 x 512 arrays. The magnetic tapes were processed on a VAX 11 780. Individual frames were corrected for flat field, and the exposures were normalized so that all frames in a movie sequence have the same average intensity. At present about eighty 512 x 512 pixel frames are being processed per day. Because SOUP used a limb tracker to generate the stabilization signal, it is necessary to align all of the frames to remove solar rotation. This is done by a full frame correlation procedure. In Figure 4 we show a portion of an original frame, which includes the sunspot of AR 4652.

RESULTS

Granulation Motions

In this section we discuss a few of the fascinating facts we are learning by studying movies of the solar photosphere. All of the movies are stored on optical video disk and are viewed using a sophisticated movie program which controls the laser disk player. Movie data include raw aligned images, one, three and five minute running averages, 1.5 and 2.5 minute differences, median filtered sequences, and results from applying various Fourier-domain filters.

In this discussion we will briefly describe the dynamics of exploding granules, of granules surrounding a the sunspot penumbra, of the penumbral filaments themselves, and of large-scale flows in the quiet sun.

Exploding Granules. Granules that appear to darken in their centers and expand radially at the end of their lives have been called exploding granules. The phenomenon appears as an expanding bright ring in a movie. They are rather rare in ground-based granulation movies, but are ubiquitous in SOUP movies of quiet sun. Except in rare cases the ring is not a complete symmetrical structure, but rather an ensemble of local brightenings which are all traveling outward from a center. We have studied a 40 x 40 arc second region intensively, in which 44 (relatively isolated) examples of exploders can be recognized in the 1600 second movie. Because it is hard to recognize incomplete events near the edge of the movie frame or the beginning or end of the sequence, probably only 2 3 of the exploders in our time sequence have been recognized. Also, due to the relatively high density of exploders some events have not been recognized because of overlap and interference. Therefore, we estimate that at least one exploder is born in a 10 x 10 arc second area every 400 seconds. Since each event expands to a diameter of 4 arc seconds on average (maximum of bright ring), at least 50 percent of the area is covered by the rapid radial expansions in this 1600 second time interval.

We are using "time-slice" images to measure and quantify the behavior individual granules. From the digital image data base, we extract the intensity pattern along a line through a feature of interest (say, parallel to the y axis) for all times in the data set to produce a y-t intensity image. Figure 5 shows three y-t images corresponding to the three lines in the conventional x-y image on the left. The exploding granules have a typical "v" shape in the time-slice, with the v opening as time increases. The opening angle of the v directly yields the velocity of radial expansion of the exploders, typically 1-2 km s.

Outflow from the Sunpot. Radial outflow of the granulation from the sunspot has been a striking new discovery. The apparent width of this collar, which immediately surrounds the sunspot penumbra, is about 5 arc seconds. Movies temporally filtered to suppress the five minute oscillations show the motion most clearly and allow an estimate of the velocities of individual granules. These range typically from 0.2 to 0.5 km s. The outward motion may be upward convection deflected by the slanted magnetic field. These measurements should be an important contribution to theoretical models of the penumbra and its effect on photospheric convection. Besides the constant advection of granules away from the spot boundary, there are also a number of bright ejections from the penumbra which travel at 2-3 km s. These events seem to be associated with elongations of the penumbral filaments. We have labeled them "streakers."

In addition to simply observing the motions from movies, we have utilized local correlation tracking to obtain quantitative information about the flow field perpendicular to the line of sight. At each pixel in the image, we measure the displacement by cross-correlation between successive frames of the movie within a 3-5 arc second window centered on the pixel. The vector displacements from 160 comparisons are used to produce an average displacement map for the entire 27 minute movie. This average map is shown overlaved on the sunspot image in Figure 6. The circle in the lower left corner gives the size of the window used for the spatial cross-correlation. The radial flow from the spot is clearly illustrated almost everywhere around the spot's circumference.

Penumbral Flows. Within the penumbra itself, the flow maps indicate that the dark filaments have a

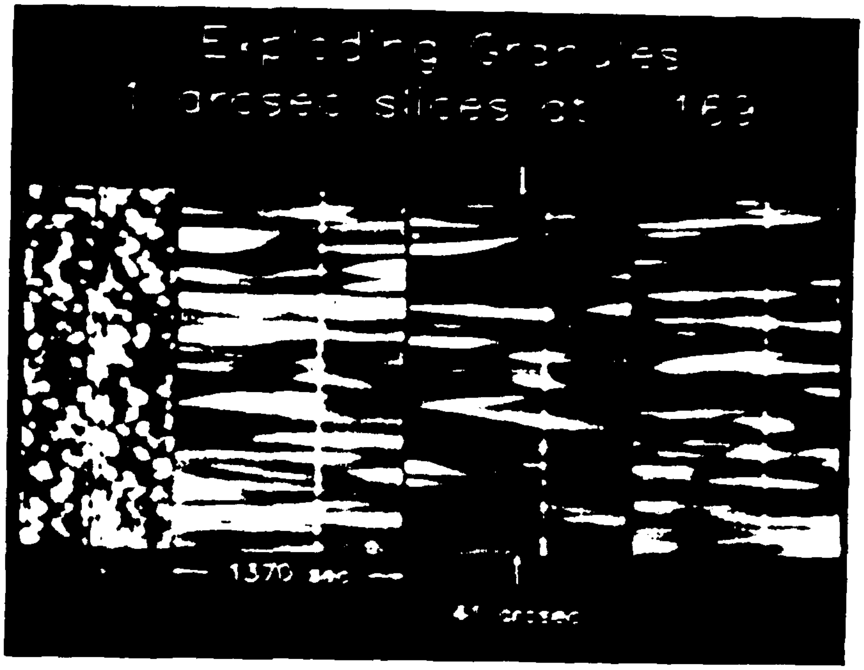

Fig. 5. Time-slice images of exploding granules

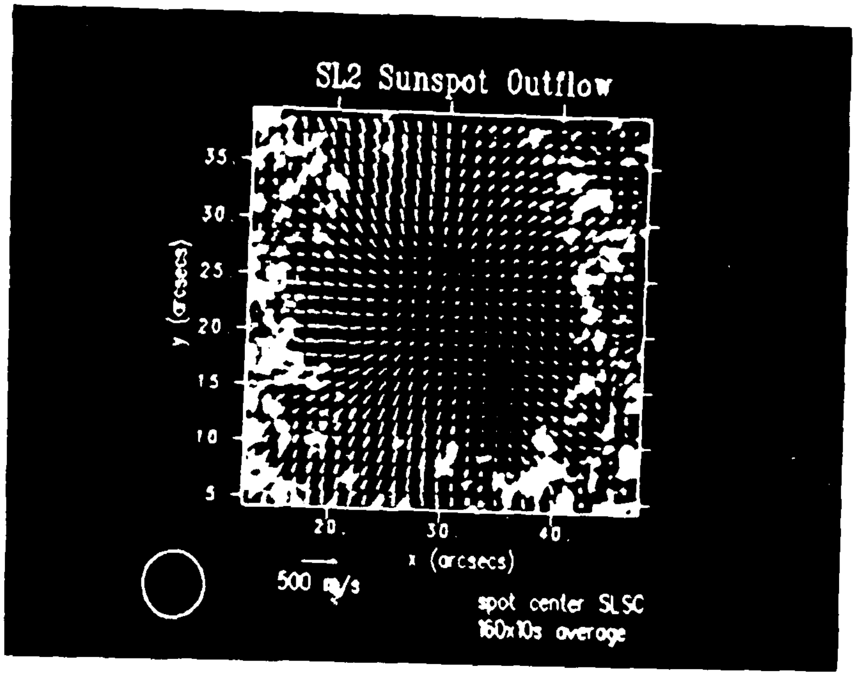

Fig. 6. Horizontal flow field for the sunspot

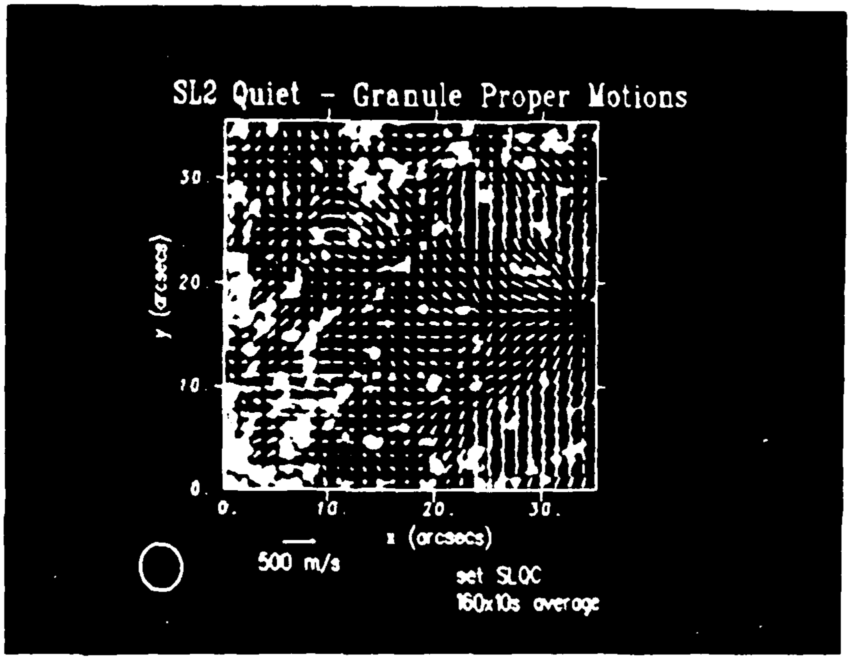

Fig 7 Flow field in quiet region

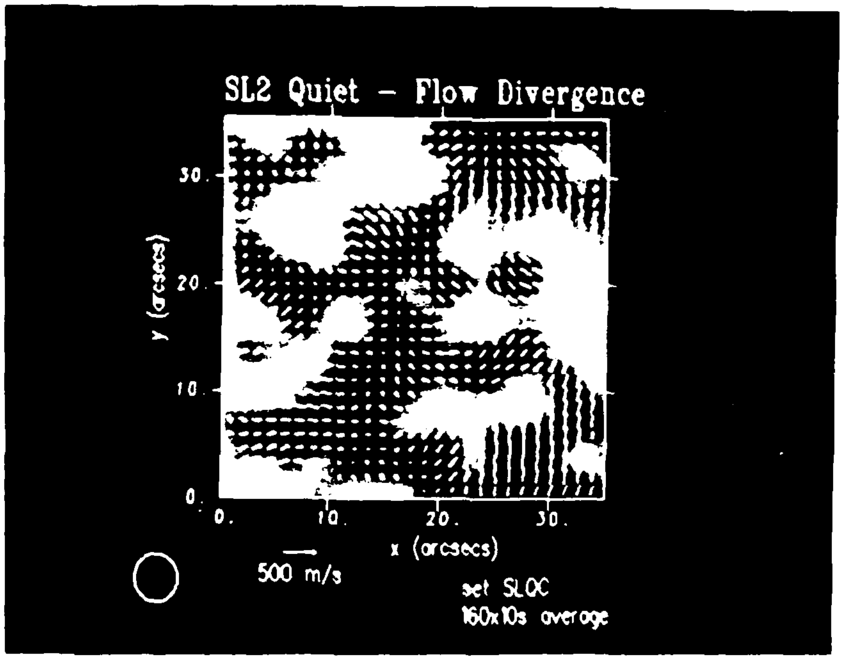

Fig 8 Divergence of the flow field

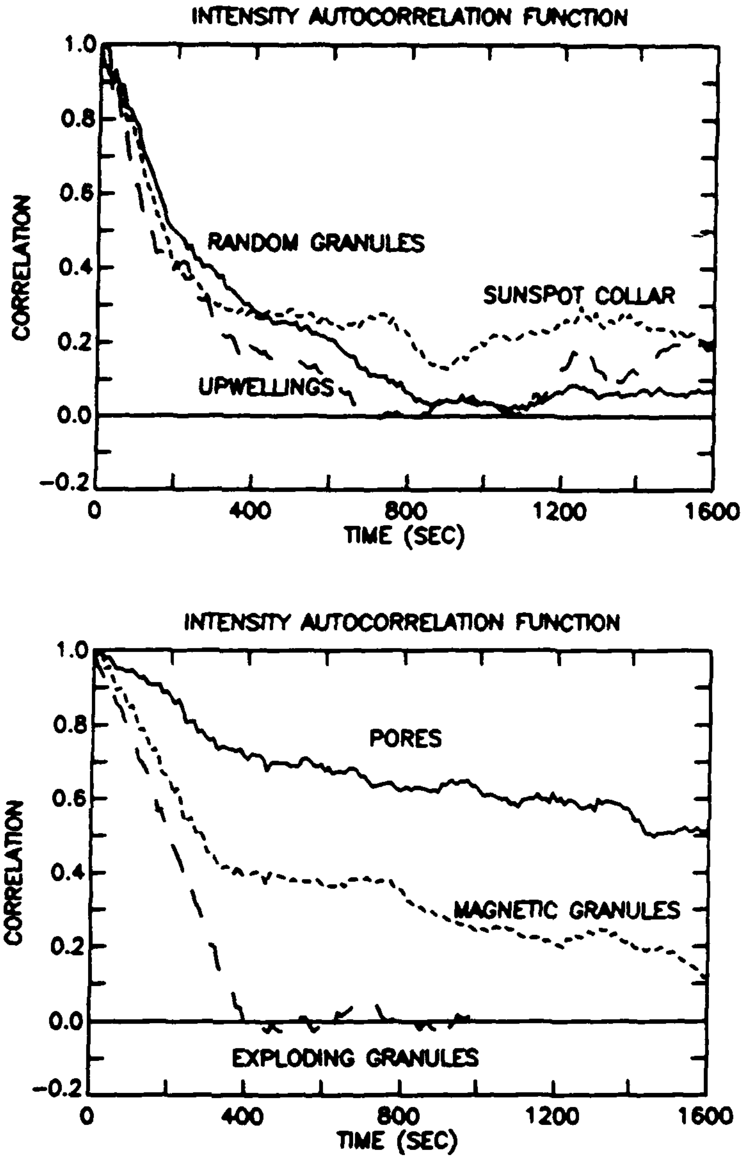

Fig. 9 Autocorrelation functions of white-light intensity

radial outflow of 0.1-0.4 km/s, while bright penumbral grains move inward at approximately the same speed. Some penumbral filaments rapidly extend and contract with rates of 1-6 km/s and amplitudes of several arc seconds. A few filaments seem to have faint extensions of 10 arc seconds or more, which appear to cover the normal photosphere as dark clouds which drift outward at several km/s. These radial motions in the sunspot vicinity are probably an extension of the Evershed flow long observed in the penumbra as a Doppler shift.

Large-Scale Motions. The five minute oscillation and the small-scale flows in granulation usually mask larger scale flow fields. However, these are clearly revealed by the correlation tracking technique. In addition to the diverging flow from the sunspot in Figure 6, we find many areas in the quiet granulation pattern which are loci of inflow or outflow. Most of the 40 x 40 arc second region of quiet sun used for the study of exploding granules is shown in Figure 7, overlayed by the average flow field. Typical velocities are in the range of 0.1-0.5 km/s. We have also calculated the horizontal divergence of the flow ($div\ v = dv_x/dx + dv_y/dy$) at each pixel. Shown in Figure 8 is gray-scale rendition of the divergence for the same quiet sun field of view; areas of positive (negative) divergence are light (dark) in this figure

TABLE 1. Correlation Lifetimes

GRANULATION LOCATION	TO 0.50	TO 0.33
RANDOM QUIET SUN	200 sec	360 sec
MAGNETIC REGIONS	280	790
PORES	>1200	>1200
SUNSPOT COLLAR	165	285
OUTFLOWING REGIONS	130	250
EXPLODING GRANULES	200	270

Cells of horizontal flow with scales corresponding to mesogranules and supergranules (5 to 30 Mm) are apparent. Velocities in the converging regions ($div\ v < 0$) are between 50 and 70 percent of those found in diverging locations, indicating a transition from largely horizontal flow in the center to largely vertical flow in the boundaries of the flow cells.

Because we have only analyzed one orbit's data (1600 s) to date, we do not know the lifetimes of these large-scale flows. However, data exist to check the flow patterns for about 15 hours.

Granulation Lifetimes

Lifetime of granules is an important physical parameter for the description of photospheric convection. In particular, it can be used to measure the effective diffusion constant associated with convection. Diffusion constants are proportional to the square of the scale length of a flow pattern divided by its lifetime. For granulation the scale has been measured in the past to be on the order of one arc second. As discussed above, there appear to be other scales in the photosphere; i.e., exploding granules (4 arc seconds) and mesogranules (10-15 arc seconds).

Traditionally lifetime has been measured using autocorrelation techniques. When a large area (100-200 square arc seconds) of quiet sun is sampled, our autocorrelation lifetime has the same shape and half width that has been measured by others. The times for the correlation function to drop to 0.5 and 0.33 of its initial value are 200 s and 360 s, respectively. However, when the autocorrelation function is measured in sufficiently small regions to isolate different types of solar atmosphere (we have used squares six arc seconds on a side), the autocorrelation lifetime varies significantly. The correlation functions for several classes of regions are shown in Figure 9, and the times for the correlation function to drop to 0.5 and 0.33 are collected in Table 1.

Quiet Sun. Quiet sun regions were selected on the basis of National Solar Observatory (NSO) magnetograms taken within a hour of SOUP observations. They were all outside the lowest contours of the magnetograms. In these regions the correlation function drops toward zero rapidly. Projected linearly the zero crossing would occur at about 350 seconds. Although the average correlation function decays monotonically toward zero, individual functions exhibit decaying oscillations about zero. These probably reflect the local structure of the global five minute oscillation phenomena superposed on the granular pattern.

Magnetic Areas. Using the NSO magnetograms as templates, regions were selected that were inside magnetic contours, but outside of sunspots or pores. Correlation functions from these regions yield a lifetime two to three times longer than that of quiet sun.

Pores. Pores are embedded in a field of smaller and brighter than average granules which last much longer than normal granulation. The correlation functions centered on pores do not drop to .5 in the time of maximum lag used in this analysis (1200 seconds).

Sunspot Collar. A prominent feature of the sunspot movies is the radial outflow of granulation discussed earlier. Correlation functions from a set of circumferentially located boxes initially drop rapidly, but then stabilize at a value near 0.3. This is probably due to relatively stable dark "channels" in the radial flow pattern.

Outflow Regions. Selected regions of quiet sun that are in the center of local outflows yield correlation functions which drop 50 percent faster than ordinary quiet solar areas, presumably due to the local expansion motions in the flow.

Exploding Granules. In regions of exploding granules the autocorrelation function has approximately the same half width as quiet sun but drops more rapidly toward zero. These regions show no tendency for recovery of the correlation function which goes to zero and stays there. This shows that no trace of the previous convective cell structure remains after the "explosion."

The variations in shape of the correlation functions from specific types of solar regions demonstrate statistically what is evident from the movies. In the quiet sun, granules move and distort significantly, are terminated by rapidly evolving events in their immediate neighborhood, and are advected by local flow patterns. In addition, their visibility is affected by the local behaviour of the five minute oscillation. On the other hand, in areas of modest magnetic field the intensity pattern is much more stable.

These correlation times are not good estimates of the average granule lifetime, due to the widely differing properties of the granulation locally and the presence of both oscillations and local flow. Therefore, we are attempting to develop effective computer algorithms for determining granule centers and recognizing the time track of a granule throughout its lifetime. Such procedures have already shown that the average quiet sun granule or granule fragment has a velocity of about one km/s. Many granules appear to move a significant fraction of their size during their lifetimes. It may turn out that the majority of granules do not die naturally, but that they are terminated by the behavior of the gas flow in the local neighborhood.

SUMMARY

We have presented some of the early results obtained during preliminary analysis of portions of the SOUP white-light data from the Spacelab 2 mission. Already, we have seen a number of new phenomena which are forcing us to rethink our long-held ideas of the nature of solar granulation and its evolution. It is quite clear that, although our spatial resolution was limited by the telescope's 30-cm aperture, the absence of turbulence in the earth's atmosphere which always degrades ground-based observations gave us by far the most outstanding time series of solar granulation ever obtained and has opened a new window through which to view the sun's surface. As we continue the data reduction, we expect to find many more surprises.

ACKNOWLEDGEMENTS

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